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Behaviour of High Performance Blended Ternary Concrete Prepared Using Alternative Materials

Research Paper

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ABSTRACT

Concrete is most widely used construction material. Traditionally, concrete is made up of cement, river sand used as fine aggregates, crushed stone aggregates used as coarse aggregates and water. Nowadays, river sand is not readily available for use in many places. To protect the river beds against the erosion and to ascertain the importance of having natural sand as a filter for ground water, periodic restrictions are being introduced by governmental authorities against the collection of river sand. Due to short supply of natural sand and increased activity in the construction sector, there is an urgent requirement of a material that matches the properties of natural sand. The ROBO sand is one of the major alternative material that can replace natural sand in concrete production, and available in abundance in various quarries as well. The objective of the present study is to investigate the effect of the physical and chemical properties of ROBO sand towards the performance of the medium strength concrete. For this, mix design was carried out for medium strength concrete considering different proportions of ROBO sand and natural sand. The fresh and hardened properties of concrete such as workability, compressive strength, splitting tensile strength and flexural strength were investigated, and the optimum replacement level of ROBO sand was determined. Also, the durability of concrete was tested for rapid chloride permeability for the concrete specimens prepared at optimum replacement level of ROBO sand. The experimental and analytical investigation carried out in the study shows that the ROBO sand can be used for the preparation of the concrete as far as the mechanical properties, durability properties the concrete are considered.

Keywords: *Concrete, Alternative materials, Nano-silica, GGBS, ROBO Sand*

INTRODUCTION

In the modern world, sustainability plays an important role in every sector of industry and infrastructure. Increasing environmental concerns such as global warming, pollution, depletion of natural resources, and stringent environmental laws have forced the industry to look into alternate ways. Strategies focusing on the recycling/ re-use of resources leading to lesser energy consumption and reduced carbon footprint are being encouraged. One of the major sectors which are making advancements in sustainable strategies is the Construction sector. The Construction sector consumes approximately 40% of all energy consumed in the economy.

Concrete is a widely used construction material owing to its low cost and good mechanical properties (Palla *et al.*, 2017). Due to rapid industrialization and infrastructure development, the rate of consumption and demand has increased many folds. However, the increased rate of consumption has led to the depletion of the natural aggregates and increased carbon emissions. Cement is the major ingredient in concrete which contributes to its carbon footprint. The cement industry

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contributes to about 5% of the total global CO_2 emission (Palla *et al.*, 2017; White *et al.*, 2000).

Several supplementary cementitious materials were incorporated into concrete to make concrete more sustainable to improve its efficiency, and assurance of its durability in order to ensure its safe service life. Over the last two decades, attempts have been made to improve the self-healing capacity of cementitious materials as well (Praveenkumar and Vijayalakshmi, 2015). By incorporating pozzolanic materials, the maintenance costs can be highly reduced, and the service life of the structure can also be improved. One of the major types of research includes replacing cement as a constituent with supplementary pozzolanic materials such as fly ash (FA), ground granulated blast furnace slag (GGBS), metakaolin, and rice husk ash etc. (Kumar *et al.*, 2011). Though, there are wide advantages in using these materials, some issues are also associated with their use, such as, delayed setting time and early-age strength, when used on a large scale.

Nowadays, Nano-particles are being used in various fields such as glass making, the process of classic photography, concrete etc. Nano-particles have a grain size of about one billionth or 10^{-9} of a meter. Due to its very small size, the properties of the Nano-particles differ a lot from materials with larger grain sizes. Thus, a lot of research is going on the utilization of nanoparticles to improve the desired properties of concrete (Mohseni *et al.*, 2016; Sanchez and Sobolev, 2010; Deb, 2008; Kahn, 2006; Sobolev and Ferrada-Gutiérrez, 2005; Drexler, 1986). When the grain size of material changes to the nanoscale, its electrical conductivity, optical absorption, chemical reactivity and mechanical properties change. The main reasons attributed to this change are increased relative surface area and dominance of Quantum effects. Due to the increased relative surface area of the Nano-particles, there is an increase in chemical reactivity. Therefore, some Nano-particles are used as catalysts too (Najigivi *et al.*, 2013; White *et al.*, 2000). Due to dominance of Quantum effects, the optical, magnetic or electrical properties of the material changes (Najigivi *et al.*, 2013; Patel, 2012; Lin *et al.*, 2008; White *et al.*, 2000). Based on literature, different Nano-particles are used in various percentages (0.2% to 12% of the weight quantity of cement) in concrete to improve its durability (Wang, 2017; Morsy *et al.*, 2011).

The existing research on nanoparticles was mainly concentrated on mechanical properties of concrete (Campbell-Allen and Thorne, 1963; Zhang *et al.*, 2015; Mukharjee and Barai, 2014a; Mukharjee and Barai, 2014b; Khan, 2002). In most of the studies, the effect of inclusion of nanoparticles on concrete were studied. Not much research focusing on microstructural and durability properties of nanoparticles mixed with blended alternative materials like GGBS and ROBO sand has been carried out for concrete production.

In the present study, the effect of replacement of natural aggregates with GGBS and ROBO sand mixed with Nano-sillica in concrete was investigated. Various proportions of Nano-silica ranging from 1% to 5% along with GGBS and ROBO sand were used in the study. Cement was replaced by GGBS from 0% to 60% at an equal increment of 15%. However, ROBO sand was used as a coarse aggregate to replace natural coarse aggregates. The durability of the concrete specimens was tested based on Chloride penetration test, Acid attack test, and mechanical properties were assessed based on Compressive strength, split tensile strength and flexural strength tests.

The study shows that the mechanical properties of GGBS and ROBO sand concrete were improved by adding Nano-particles. Firstly, this can significantly reduce the formwork span, which in turn, will reduce the cost of project. Secondly, due to its high specific area and ultra-fine size, it the durability properties of concrete were improved, which can ultimately increase the service life and maintenance cost of the structure.

This research will provide better understanding about the utilization of nanoparticles and supplementary cementitious material in concrete. Application of supplementary cementitious material in concrete provides great benefit to the society which ultimately reduces the CO_2 emission related to ordinary Portland cement.

MATERIALS AND METHODS

Ordinary Portland Cement

43 grade Ordinary Portland cement (OPC) conforming to BIS: 12269-1987 and equivalent to Type-I (ASTM) with a specific gravity of 3.15 and a Blaine fineness of 350 m^2/kg was used in this study. The chemical and physical properties of ordinary Portland cement are reported in Table 1 and Table 2 respectively.

Table 1. Chemical Properties of Cement

Components	**SiO_2**	**CaO**	**Al_2O_3**	**Fe_2O_3**	**MgO**
Value (%)	22.12	56.12	5.2	3.11	6.45
Components	**SO_3**	**K_2O**	**Na_2O**	**Loss on ignition**	
Value (%)	3.77	0.88	0.19	2.16	

Table 2. Chemical Properties of Cement

Property	**Value**
Normal consistency	30%
Soundness	1.0 mm
Initial Setting time	40 minutes
Final setting time	450 minutes
Specific Gravity	3.15

Natural Aggregates

Natural siliceous washed sand having a maximum nominal size of 4.75 mm, with a gradation falling within the limits of the Grading Zone III as per the specifications of BIS: 383-1970 was used as a fine aggregate. Two fractions of well graded washed ROBO sand with a nominal size of 20-12.5 mm and 12.5-4.75 mm as per the specification of BIS: 383-1970 were used as coarse aggregate and their gradation is shown in Fig. 1. The bulk density and void content for both coarse and fine aggregates were measured as per ASTM C29 (2017). The physical properties of the aggregates are reported in Table 3.

Nano-Silica

Silicon dioxide (SiO_2) Nano particles or Nano-silica, has low toxicity. Increased strength, flexibility, workability, durability, viscosity of fluid phase are some of the advantages of using Nano-silica in concrete production.

Table 3. Physical properties of aggregate

Physical properties	**Aggregate**		
Aggregates Type	Fine	Coarse (ROBO Sand)	
Particle Size	4.75 mm	20 mm	12.5 mm
Specific gravity	2.62	2.75	2.75
Bulk Density (Kg/m^3)	1780	1590	1420
Water absorption capacity (%)	1.0	0.5	-
Void content (%)	32.1	42.2	48.4
Fineness Modulus	2.9	8.15	6.1
Grain shape	Spherical	Angular and irregular	

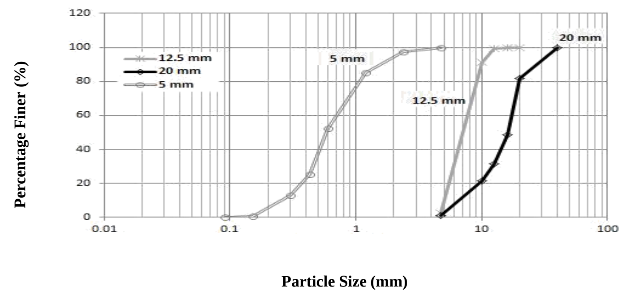

Fig.1. Gradation curves for coarse and fine aggregates

DESIGN MIX AND EXPERIMENTAL SETUP

The design mix calculations of M40 concrete with various percentages of nano-silica, GGBS and ROBO Sand have been done as per the specifications of ACI Method by American Concrete Institute (Gambhir, 2011) and the results are presented in Table 4. Description of various test conducted on different type of concrete specimens is as follows.

Compressive Strength Test

Concrete cubes of 10 cm × 10cm × 10 cm in size were kept immersed in water at 20˚ C in a curing tank after 24 hours of casting. The samples were tested for compressive strength at 7, 28 and 90-days interval. Compressive strength test was carried out on three specimens for each type of concrete as per the specifications of ASTM C39 (2021).

Table 4. Various Design Mixes Proportions

No.	Sample ID	Sample Description	W/C ratio	Cement (Kg/m^3)	GGBS (Kg/m^3)	Nano-particles (Kg/m^3)	Fine Aggregates (Kg/m^3)	ROBO Sand (Kg/m^3)	Super-plasticizer (Kg/m^3)
1.	CC	Plain Cement Concrete prepared using ROBO Sand without GBFS and Nano-silica	0.45	420	0	0	685	1134	2.5
2.	CC- 15	15% Cement replaced by GBFS	0.45	357	63	0	685	1134	2.5
3.	CC- 30	30% Cement replaced by GBFS	0.45	294	126	0	685	1134	2.5
4.	CC- 45	45% Cement replaced by GBFS	0.45	231	189	0	685	1134	2.5
5.	CC- 60	60% Cement replaced by GBFS	0.45	168	252	0	685	1134	2.5
6.	CCPN1	1% Cement replaced by Nano-silica and 45% Cement replaced by GBFS	0.45	231	189	4.2	685	1134	2.5
7.	CCPN2	2% Cement replaced by Nano-silica and 45% Cement replaced by GBFS	0.45	231	189	8.4	685	1134	2.5
8.	CCPN3	3% Cement replaced by Nano-silica and 45% Cement replaced by GBFS	0.45	231	189	12.6	685	1134	2.5
9.	CCPN4	4% Cement replaced by Nano-silica and 45% Cement replaced by GBFS	0.45	231	189	16.8	685	1134	2.5
10.	CCPN5	5% Cement replaced by Nano-silica and 45% Cement replaced by GBFS	0.45	231	189	21	685	1134	2.5
11	CCPN6	6% Cement replaced by Nano-silica and 45% Cement replaced by GBFS	0.45	231	189	25.2	685	1134	2.5

Split Tensile Test

The concrete specimens of diameter 100 mm and height 150 mm were kept immersed in water at 20˚C in a curing tank after 24 hours of casting. The cylindrical specimens were tested for split tensile strength at 7, 28 and 90 days in a universal testing machine. Three samples were tested for each type of mix. These tests were conducted as per the specifications of ASTM 496 (2017).

Flexural Strength Test

The concrete prisms of size 100 mm × 100 mm × 150 mm were kept immersed in water at 20˚C in a curing tank after 24 hours of casting. The solid samples were tested for flexural strength at 7, 28 and 90 days. These tests were performed as per the specifications of ASTM 293 (2016). Three samples were tested for each type of concrete.

Rapid Chloride Penetration Test

The Rapid chloride penetration test (RCPT) provides a quick feedback on the effect of mineral additives, in this case, Nano-particles and Pozzolanic materials on the chloride ions penetration resistance. Concrete cylindrical specimens of 50 mm height and 100 mm diameter were subjected to initial wet curing for 28 days and were then used for the RCPT. The test was carried out as per ASTM C1202-19 (2019). The concrete discs were coated with epoxy from the sides and when the epoxy dried, the samples were placed in a vacuum chamber for 3 hours. The specimens were then placed in the testing device where the two uncoated sides of the specimen are in contact with two different cells. One side of the concrete disc was in contact with a cell filled with 3% (by weight) of sodium chloride (NaCl) solution used as anode, while the other uncoated side of the concrete disc is in contact with a cell filled with 0.3 N Sodium Hydroxide (NaOH) solution used as cathode.

RESULTS AND DISCUSSION

Compressive Strength

The variation of compressive strength among different types of concrete specimens tested at 7, 28 and 90 days is presented in Fig.2. The concrete sample with 45% of pozzolanic material (GGBS) showed a compressive strength at par with the control mix. Since, one of the objectives of this research was to find a suitable replacement for cement, the baseline percentage of replacement of cement with GGBS was taken as 45% for further testing with nano-particles.

For all the samples prepared using nano-particles, an increase in the compressive strength was observed. At an initial stage, the compressive strength of concrete specimens prepared with nanoparticles showed a slight reduction in strength in comparison to the conventional mix. This reduction in strength can be attributed to the delayed onset of pozzolanic reaction. However, the concrete specimens cured for 28 days and 90 days showed increased strength in comparison with conventional concrete. The compressive strength of specimens prepared with 4% Nano-particles achieved higher strength in comparison with the rest of the specimens at all curing ages. The increased strength in specimens prepared with 4% Nano-silica was observed to be 15% in comparison to conventional concrete specimens cured for 28 days.

The nanoparticles act as a filler material thus increasing the particle packing density of concrete and also consuming the calcium hydroxide present in the concrete samples by forming additional calcium silicate hydrate gel. An increase of nanoparticles beyond 4% had not contributed to the compressive strength gain due to saturation. The formation of CSH gel reduces the calcium hydroxide content in the concrete mix thereby enhancing the microstructure and reducing the porosity in the concrete mix. However, excess utilization of nanoparticles absorbs more amount of water and it stops the hydration process. An excess amount of silica particles does not allow the cement to consume water and it forms a layer on the cement making cement inaccessible for water. Excessive silica content forms a weak layer in concrete specimens and thus ultimately reduces the strength properties of concrete specimen.

Split Tensile Strength

The results of the split tensile strength test of concrete specimens tested at 7, 28 and 90 days of curing are shown in Fig.3. The results showed a similar trend as that of compressive strength. Utilization of nanoparticles in varying percentages ranging from 0 to 5% improves the split tensile strength of concrete at all curing ages. Out of all specimens, the one with 3% nanoparticles achieved higher strength gain up to 10%, 10.5% and 9% at 7, 28 and 90 days curing ages respectively in comparison to the control mix. Beyond 3%, on further addition of nanoparticles, a reduction in strength gain was observed due to saturation. Improvement in the strength of concrete specimens can be attributed to the formation of secondary Calcium silicate hydrate gel by consumption of the calcium hydroxide.

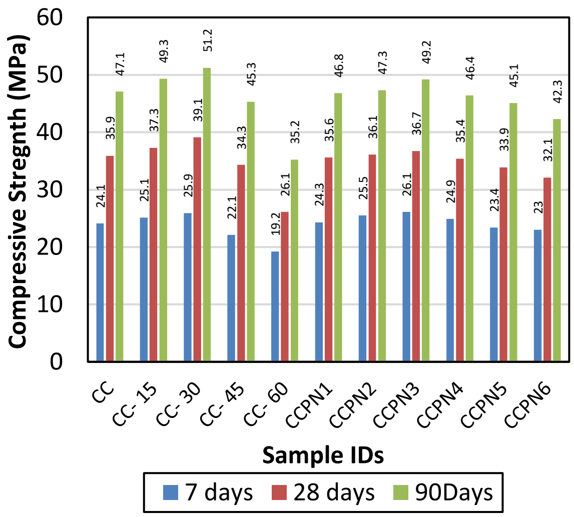

Fig.2. Variation of Compressive Strength in Different Concrete Specimens (values of strength

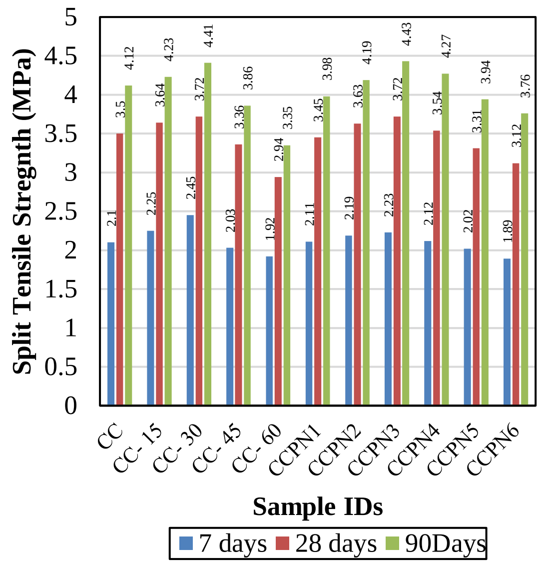

Fig.3. Variation of Split Tensile Strength in Different Concrete Specimens

Flexural Strength

A similar trend as that of compressive strength was observed for flexural strength (see Fig.4). Pozzolanic material was added up to 45% as a partial replacement to OPC in the concrete mix. As a result, a slight improvement in the flexural strength was observed for all the specimens tested at 7, 28 and 90 days. Moreover, further improvement in flexural strength was observed by adding 45% GGBS with various percentages of nanoparticles as a partial replacement of OPC for all the specimens. A maximum value of flexural strength was observed for specimens prepared with 3% Nano-particles. No significant increase in flexural strength was observed with a further increase of Nano-particles.

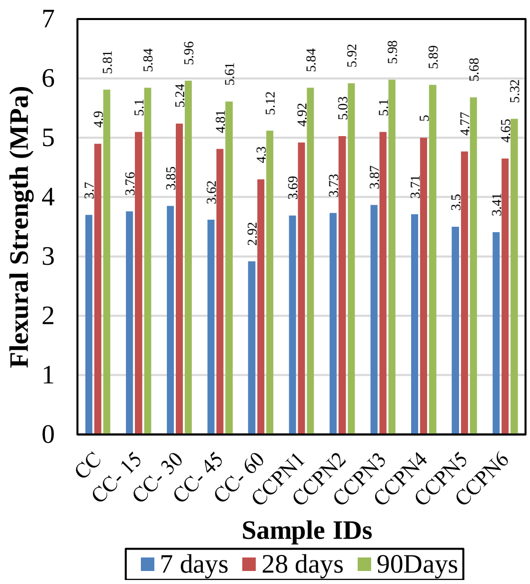

Fig.4. Variation of Flexural Strength in Different Concrete Specimens

Rapid Chloride Penetration Test

The concrete specimens cured for 14 and 28 days were subjected to rapid chloride penetration test (RCPT) as per the specifications of ASTM C1202-13 (2013) to assess the electrical conductance of the control concrete mix and mixes made with Nanoparticles and Pozzolanic materials. Overall, specimens prepared with Nano-particles and Pozzolanic material showed a low chloride permeability, while the control mix indicates a moderate chloride permeability at a curing age of 14 and 28 days based on the total charge passed as specified by ASTM C1202-13 (2013).

It was observed that for both the control and blended mixes with 45% pozzolanic and various replacement of Nanoparticles, the total charge passed has decreased when the curing time increased from 14 days up to 28 days. This can be attributed to the continuous formation of solid hydrate products leading to increased strength and subsequent reduction in the permeability. The incorporation of both Nanoparticles and Pozzolanic materials showed a clear decrease in the amount of electrical current passed through the concrete disc during the 6 hours of testing time.

At 10% addition of Pozzolanic material to the concrete mix, total charge passed reduced to 5.1% and 8.4% for specimens cured at 14 and 28 days respectively as compared to the control mix with 100% OPC. A significant reduction in permeability was observed for specimens prepared with Nano-particles and 10% Pozzolanic material. Moreover, a sharp decrease in the specimen's permeability and, ultimately, reduction in chloride penetration was observed with increase in percentage of Nano-particles, especially after 28 days curing.

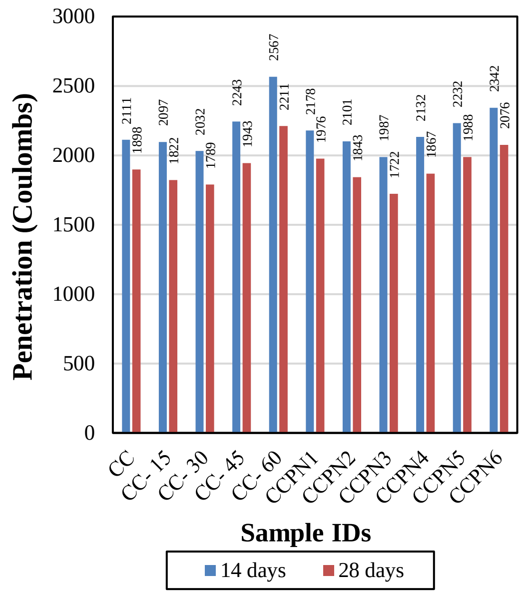

Fig.5. Chloride penetration level of nanoparticles and GGBS incorporated concrete sample

CONCLUSION

Based on the study following conclusions are drawn:

1. It was observed that compressive, flexural and split tensile strengths increase due to addition of GGBS as a partial replacement to OPC.
2. The combination of GGBS with various percentages of Nano-particles, further improve the 90 days strength of concrete.
3. This combination of ternary system with OPC, Pozzolanic materials, Nano-particles was observed to be very effective in decreasing the permeability and increasing resistant against chloride penetration as well.

4. The maximum improvement in compressive, split tensile and flexural strengths is observed on addition 3% Nano-particles as a partial replacement to OPC. Hence, 3% can be considered as the optimum percentage.
5. The findings of the results can be used to prepare PCC (plain cement concrete) using GGBS and nano-silica. However, further research is required to comment on their application in RCC (reinforced cement concrete).
6. The use of GGBS significantly reduced the amount of cement required to produce medium strength concrete.
7. The use of alternative material like GGBS as a replacement for OPC would help in reducing the carbon footprint of the cement and construction industry.
8. The utilization of ROBO Sand in concrete would reduce the demand and over mining of natural coarse aggregates from riverbeds.

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